Atmospheric energy spectra in kilometer-scale global simulations

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Tellus A: Dynamic Meteorology and Oceanography, **74**, 280–299, doi: 10.16993/tellusa.26/

ECMWF Annual Seminar, Reading, September 2022

MAX-PLANCK-INSTITUT FÜR METEOROLOGIE

Horizontal kinetic energy spectra

Synoptic scales: **k^{-3}**

- non-divergent motions (Fjørtoft 1953)

Mesoscale: **$k^{-5/3}$**

- non-linearly interacting inertia-gravity waves (Dewan 1979, VanZandt 1982)
- forward energy cascade (Lindborg 2006)
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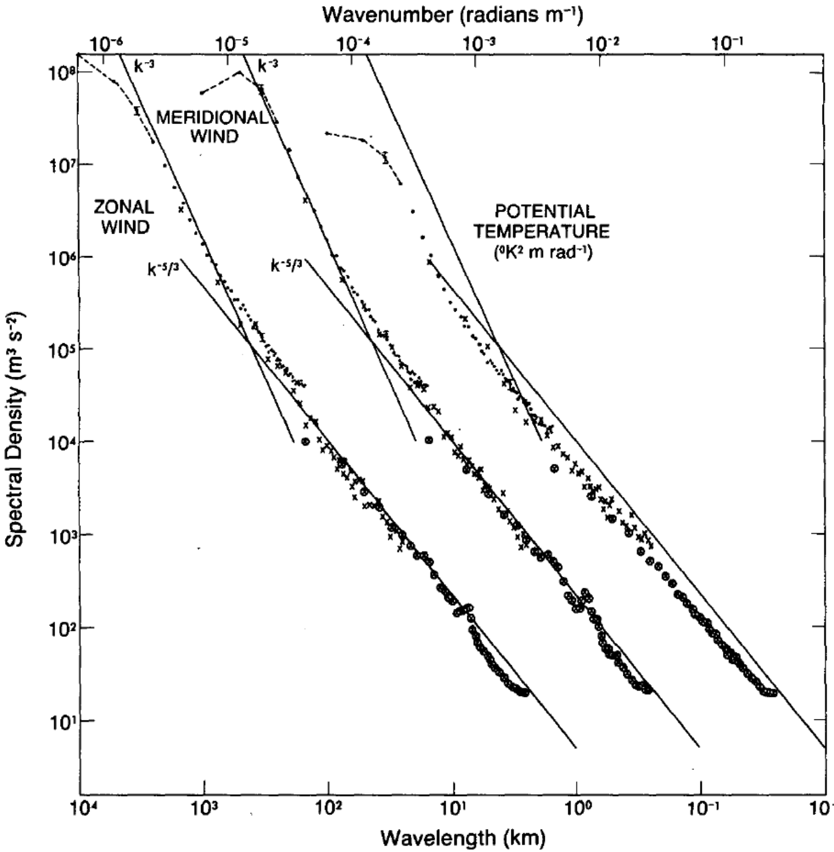

Nastrom and Gage 1985

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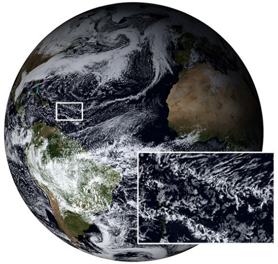
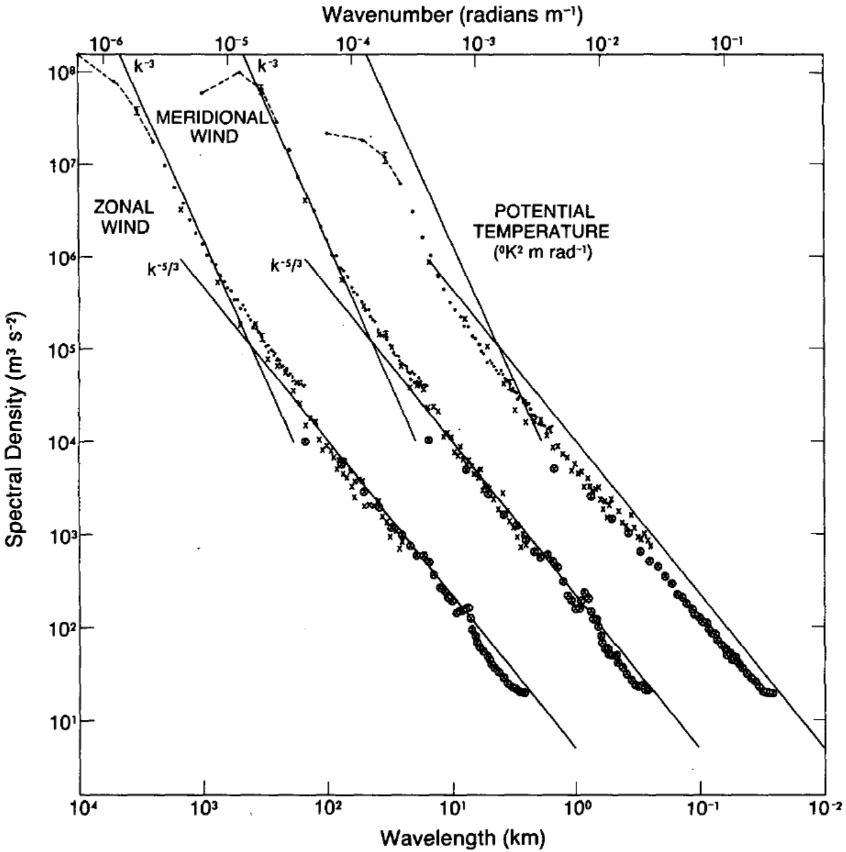
DYAMOND simulations: Δx < 9 km

☑ Dynamics of convective storms
☑ Influence of topography on circulation





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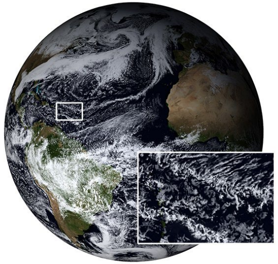

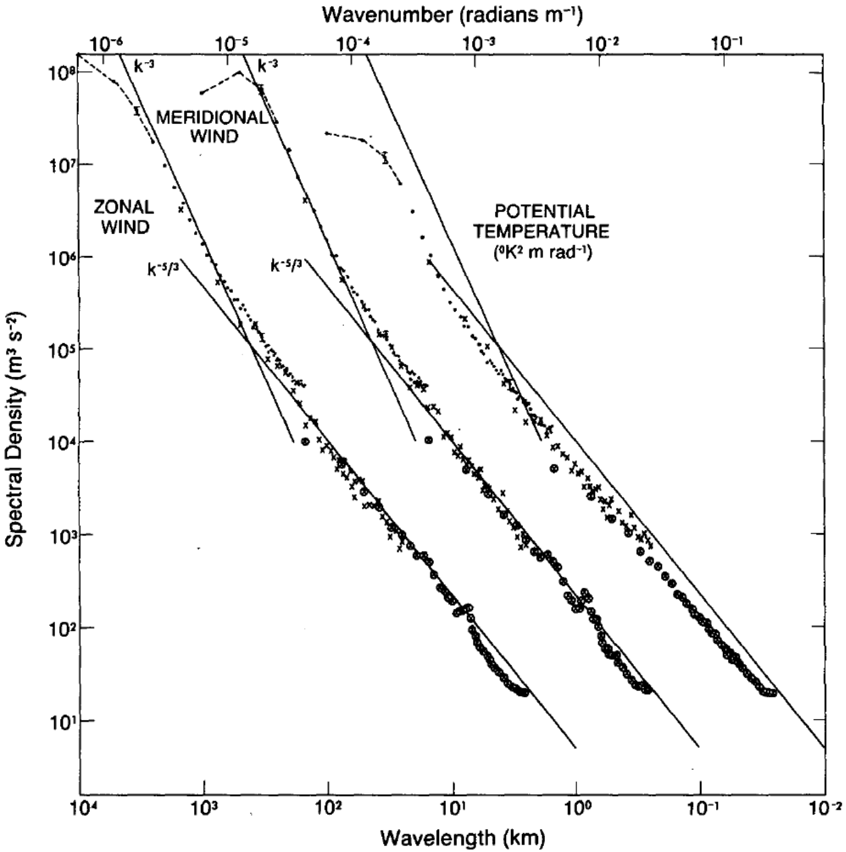

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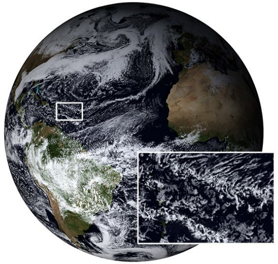
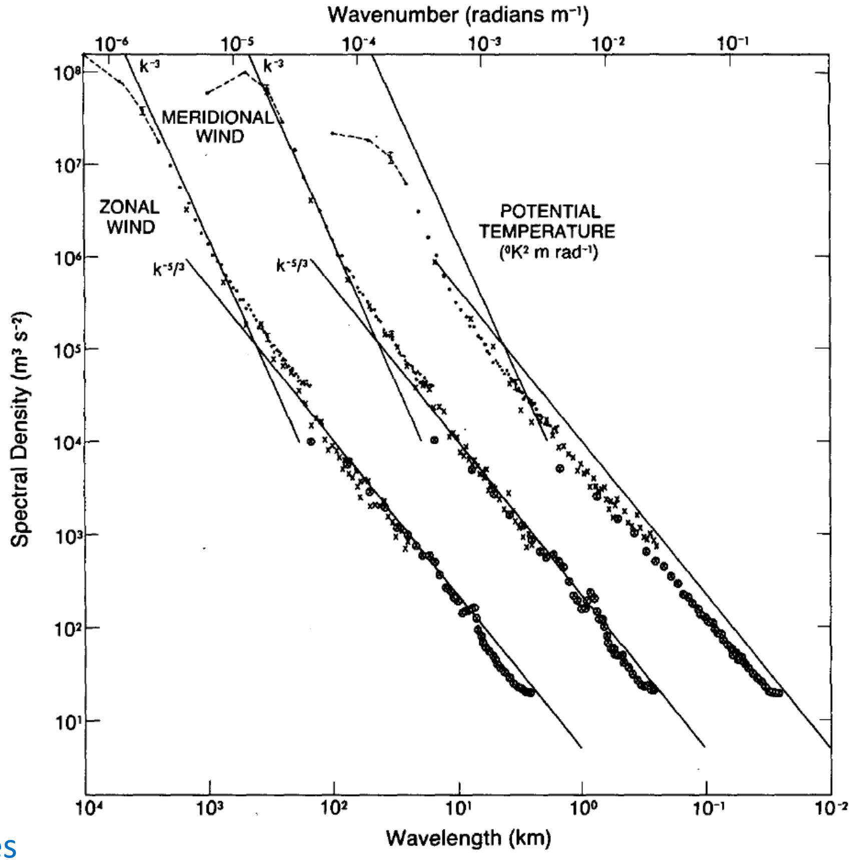


Vertical momentum and energy exchanges are to some degree modelled explicitly.

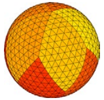


Nastrom and Gage 1985

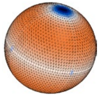
Expectations based on DYAMOND summer

ICON
Δx: 5 & 2.5 km

NICAM
Δx: 7 & 3.5 km



IFS
Δx: 9 & 4 km



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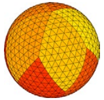

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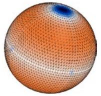
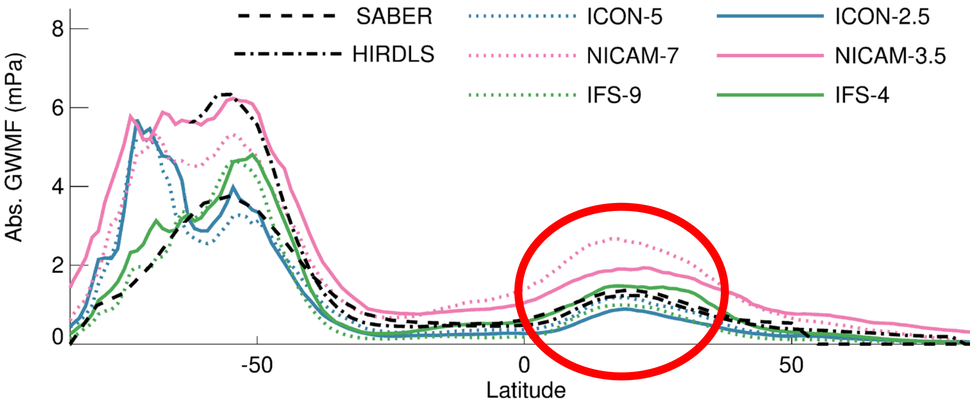


Zonal mean absolute GWMF:
Simulations differ



Stephan et al. 2019 JAS

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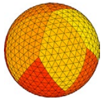

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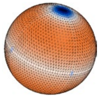

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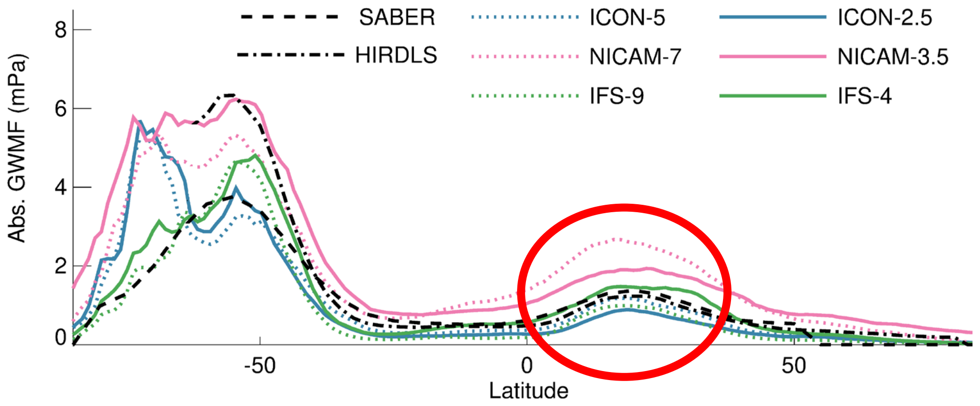
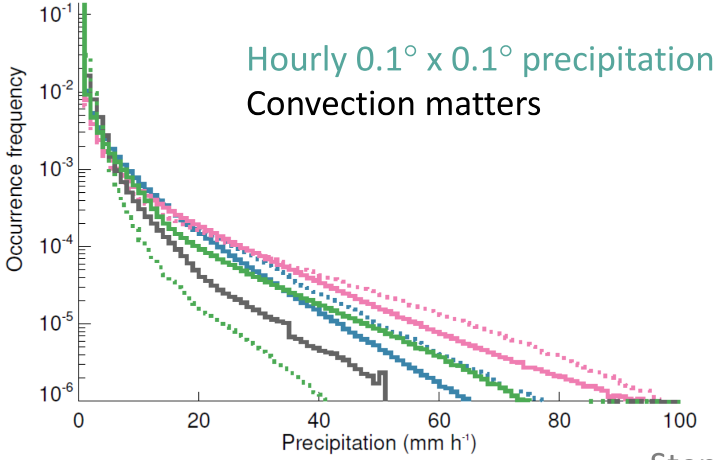


Hourly 0.1° x 0.1° precipitation at 0° – 40° N:
Convection matters



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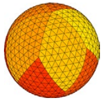

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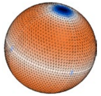

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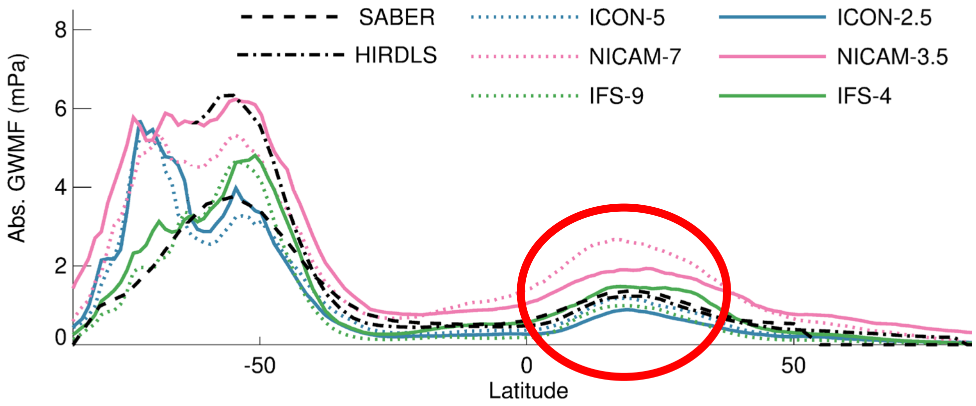
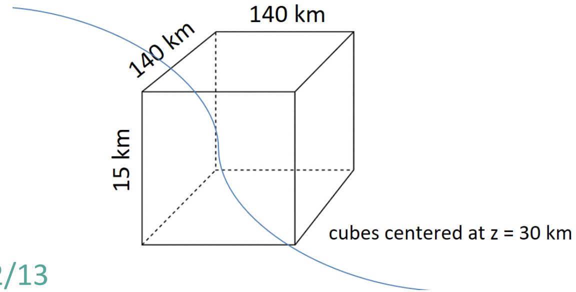


Limitations of S3D (Lehmann et al. 2012):

- Focus on predefined wavelengths
- Imperfect filtering of gravity waves
- Focus on a single height level



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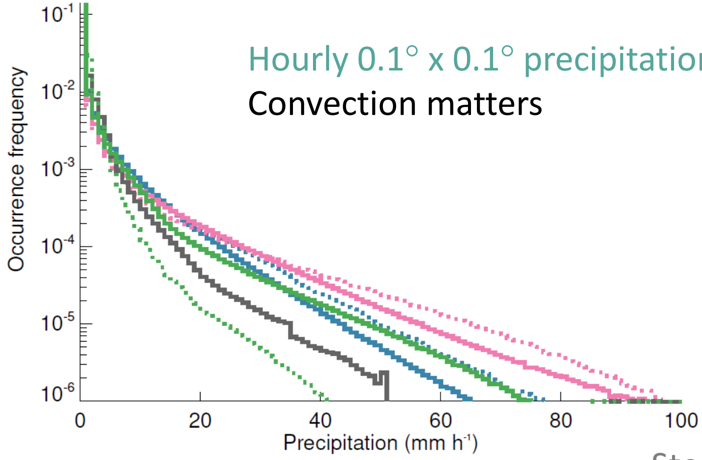

Stephan et al. 2019 JAS

Today: a different perspective

Normal mode function (NMF) decomposition:
Using the software package MODES (Žagar et al. 2015)
It projects the **3D** fields of geopotential height and horizontal winds onto an orthogonal set of NMFs.

Properties:
- the NMFs are eigensolutions to the linearized primitive equations
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This is the first time NMF decomposition is used for inter-comparing high-resolution models.

- How closely do the models produce the canonical spectra?
- What is different in terms of total energy levels / synoptic and sub-synoptic slopes / the crossing scale ?
- Can we understand the origin of these differences?

The simulations

Initialized 20th January 2020 with the global 9 km meteorological analysis from the ECMWF
Freely evolving until 1st March 2020.

Simulation	$\sqrt{A_{mean}}$	H_t	Grid	Coupled	Conv.	BL	SSO	comments
IFS-9	9	80	Octo	yes	F	K	yes	hydrostatic
IFS-4	4.5	80	Octo	yes	S	"	"	
ICON-nwp	2.5	75	Icoso	no	-	TKE	no	
ICON-sap	5	"	"	yes	"	S	"	
ICON-sap+	"	"	"	yes	"	"	"	continuation of ICON-sap
ICON-vdu	"	"	"	no	"	TTE	"	
ICON-vdc	"	"	"	yes	"	"	"	
ICON-vda	"	"	"	yes	"	"	"	increased albedo
GEOS	3	80	Cube	no	F	K	yes	deep plumes disabled
SHiELD	3	40	"	mixed-layer ocean	S	TKE	yes	
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K: diagnostic eddy diffusivity
TKE: prognostic turbulent kinetic energy
TTE: prognostic turbulent total energy
S: Smagorinsky scheme
SHOC: Simplified Higher Order Closure

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Overly diffusive

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Convection

Expectations based on DYAMOND summer

Stronger and deeper convection is usually associated with stronger vertical velocities and larger gravity wave momentum flux.
(Müller et al. 2018; Stephan et al. 2019a,b)

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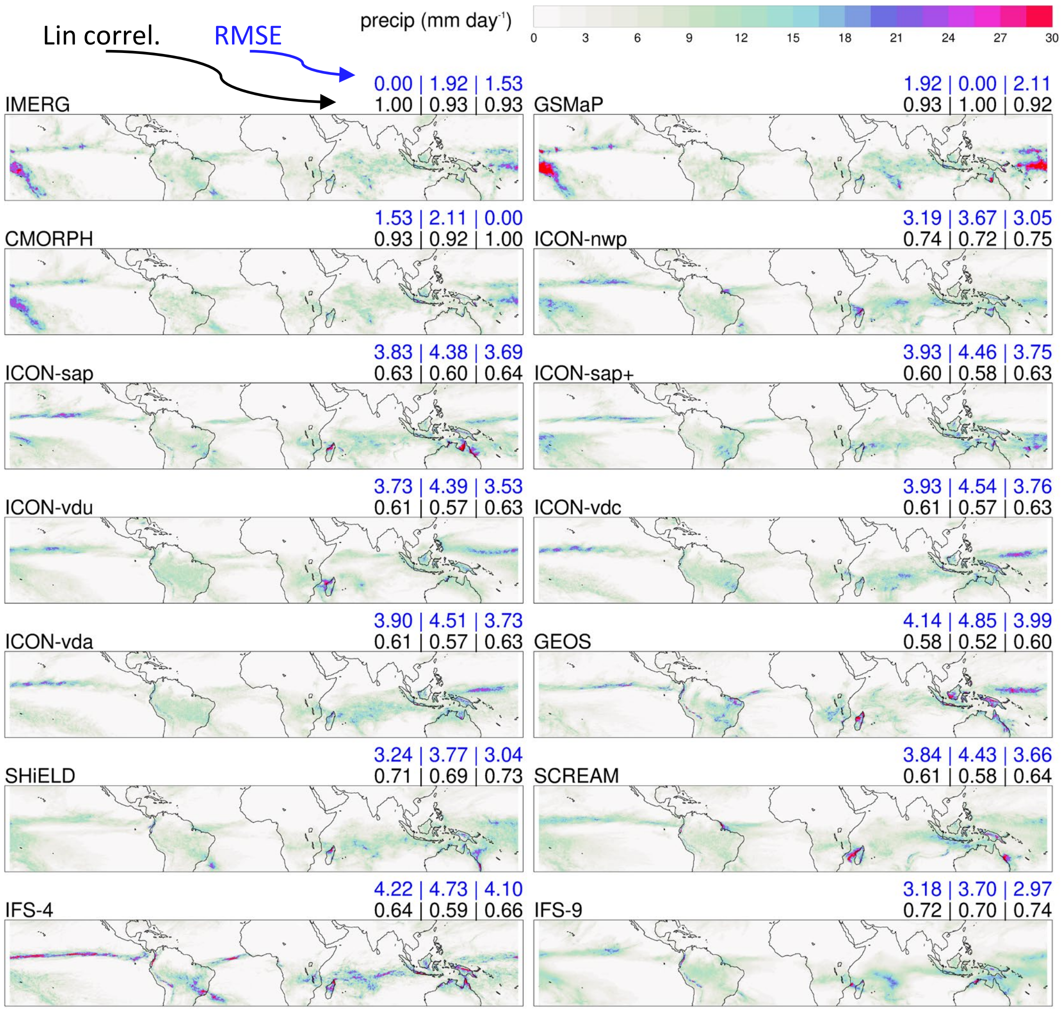

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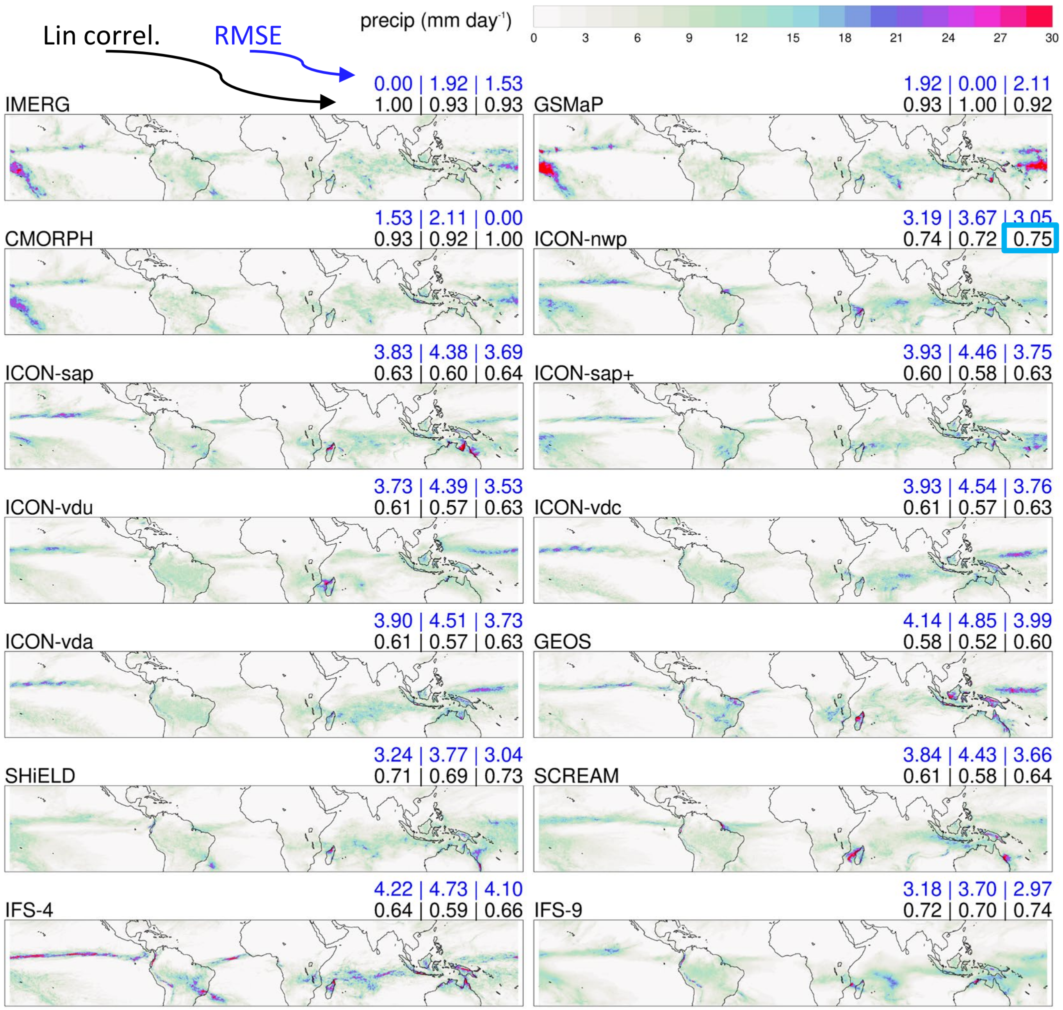

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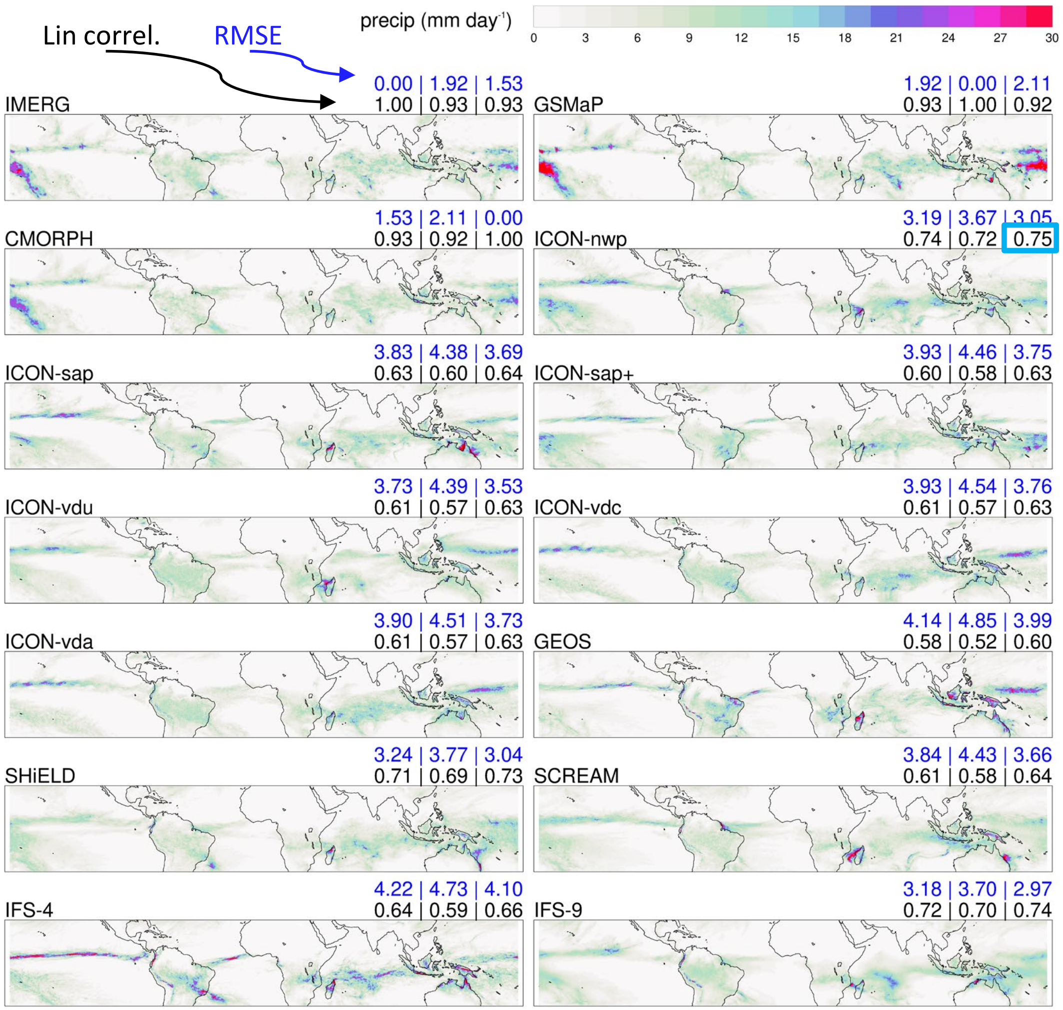

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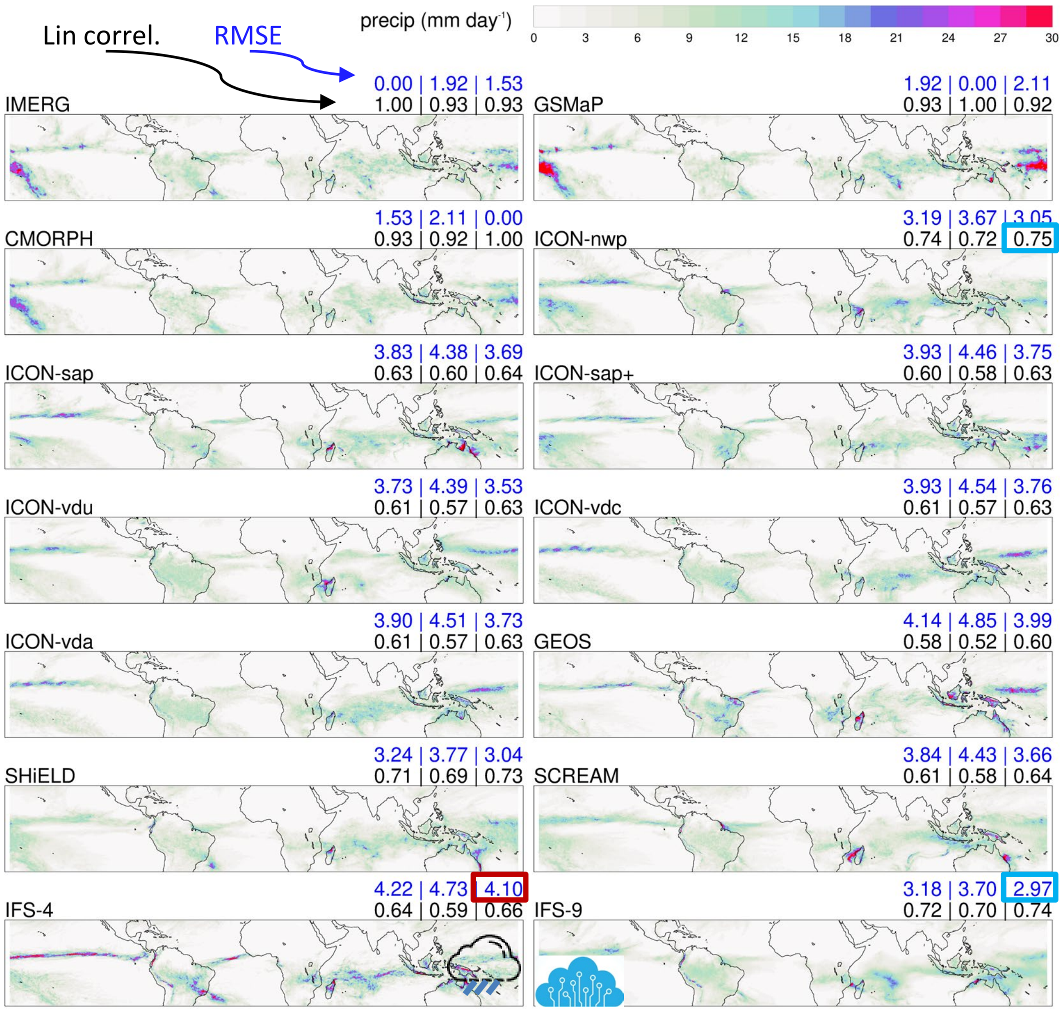

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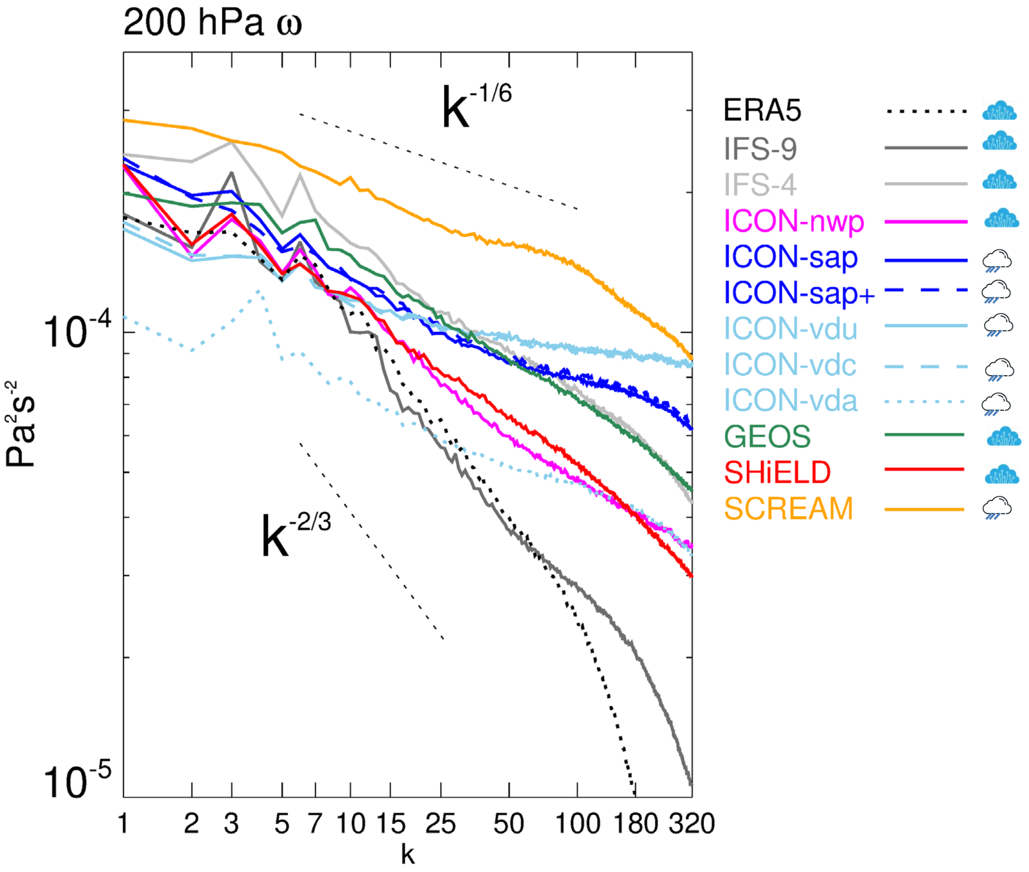
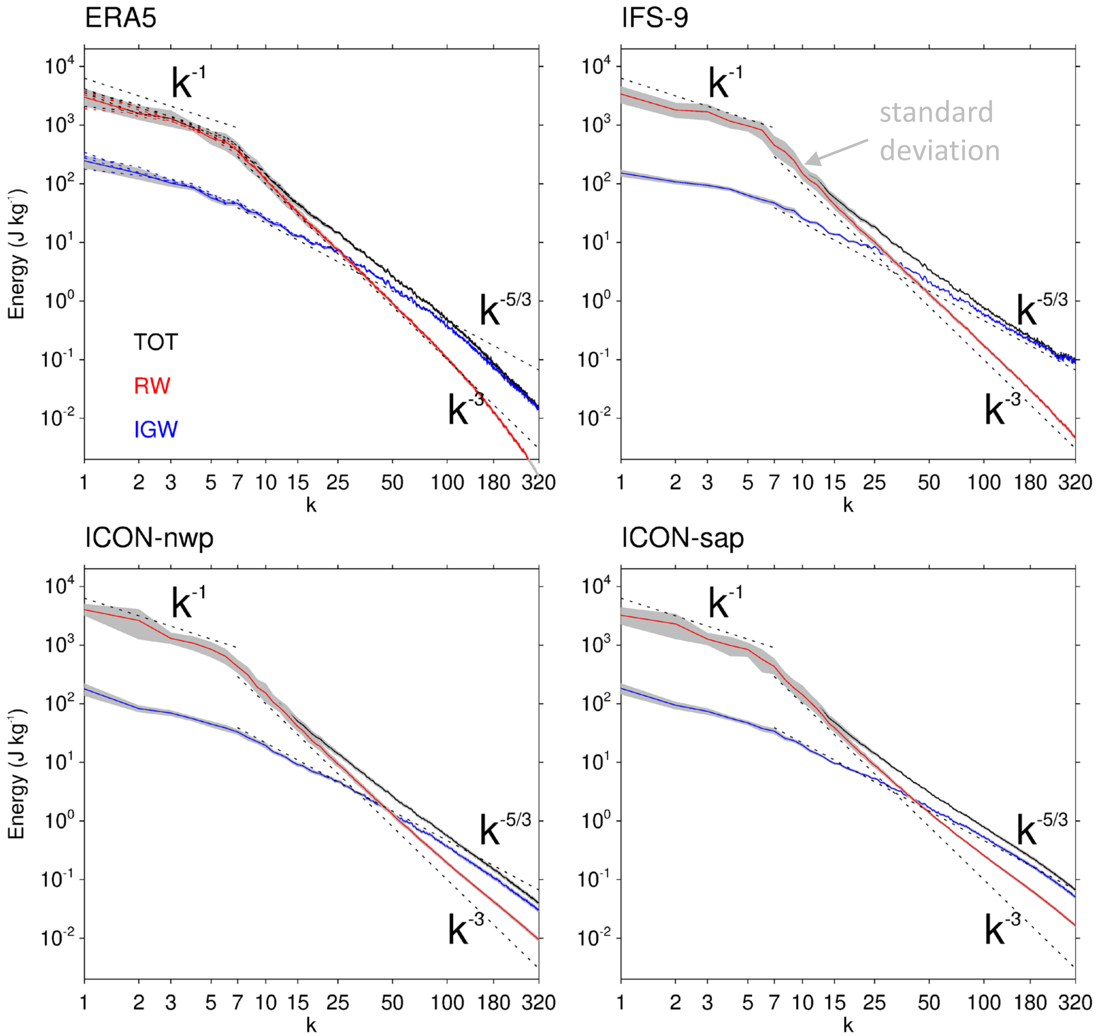
Model formulation ( ) affects the small scales.



Energy spectra

ERA5: Little interannual variability

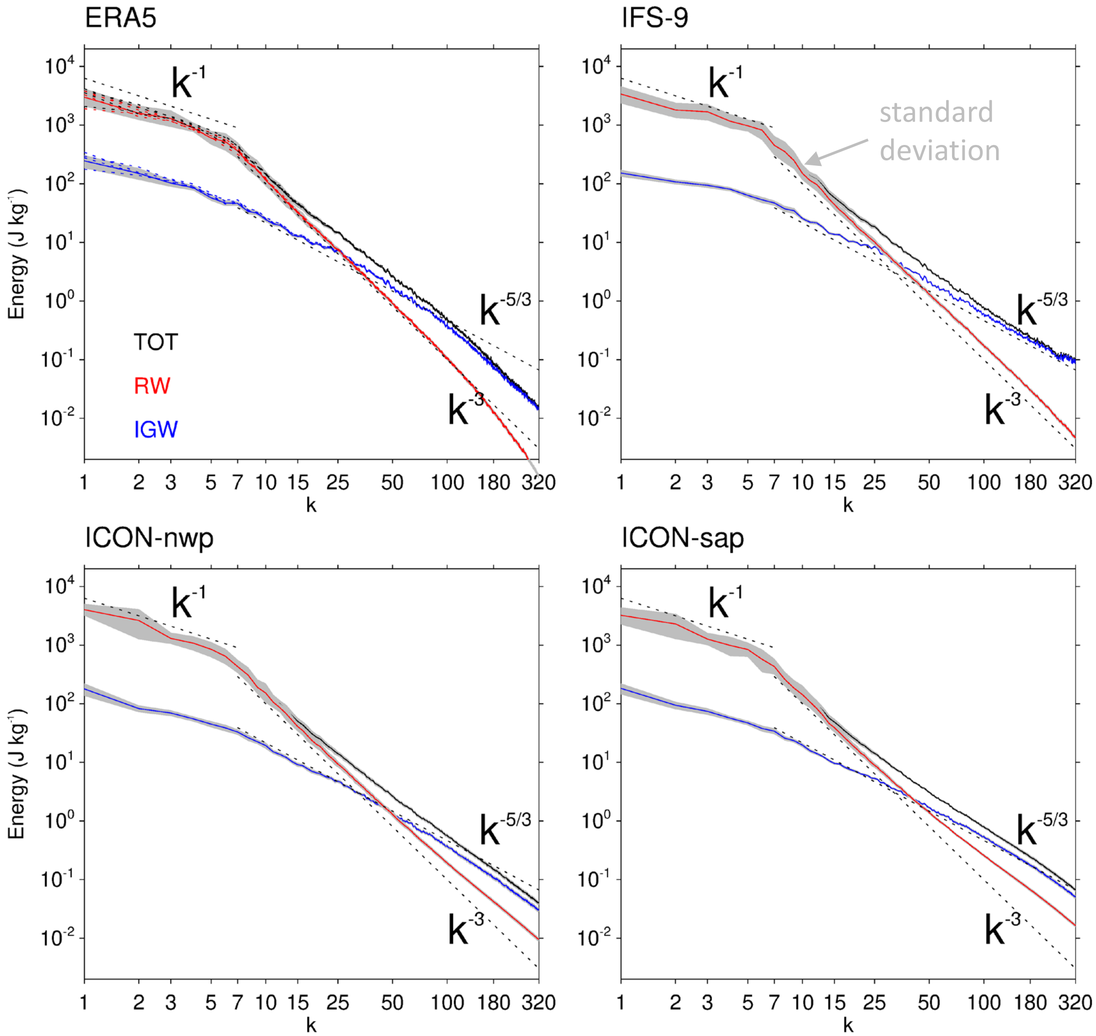


Energy spectra

ERA5: Little interannual variability

Planetary scales: still depend on initialization.
We focus on k > 7.

Spectra are robust footprints!
(Boer and Shepherd 1983; Malardel and Wedi 2016)



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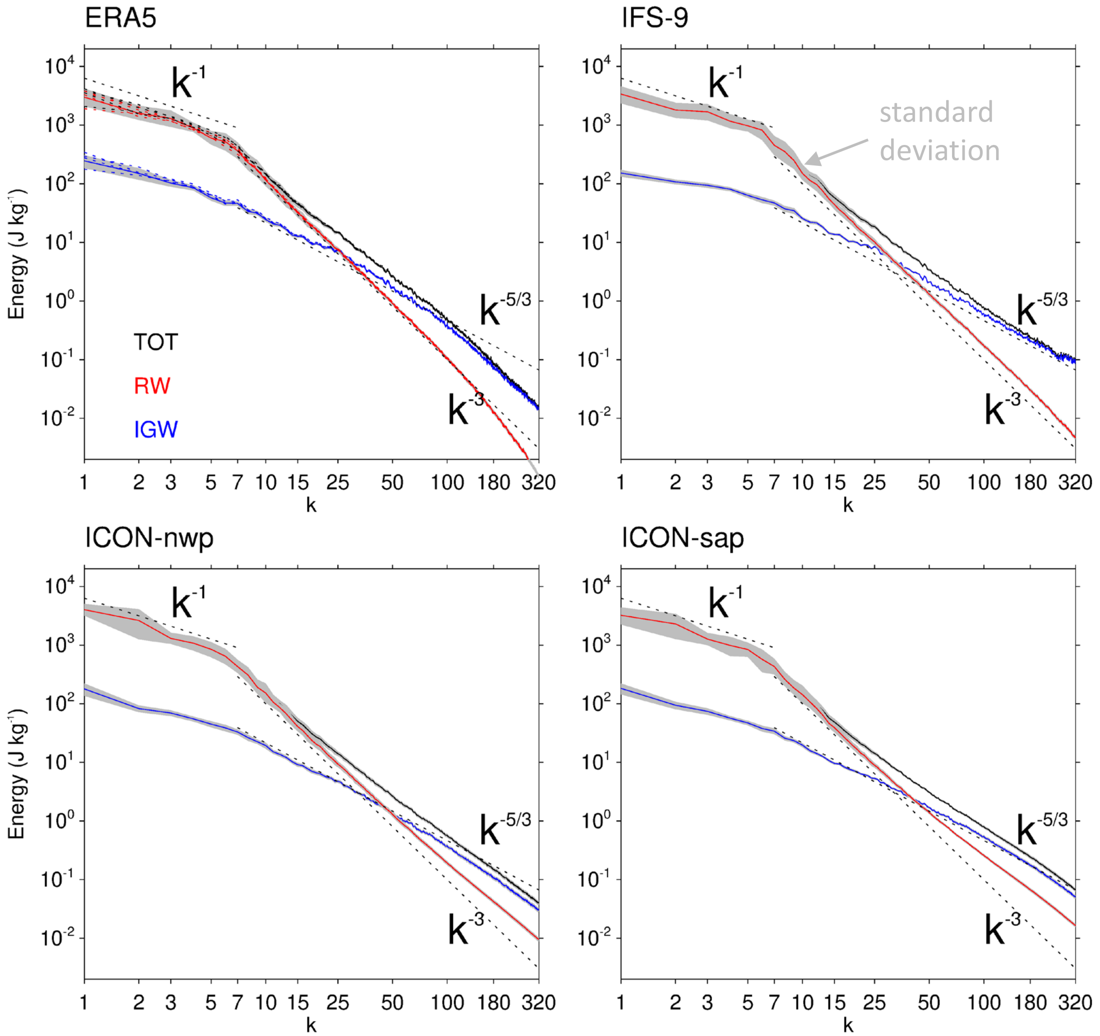

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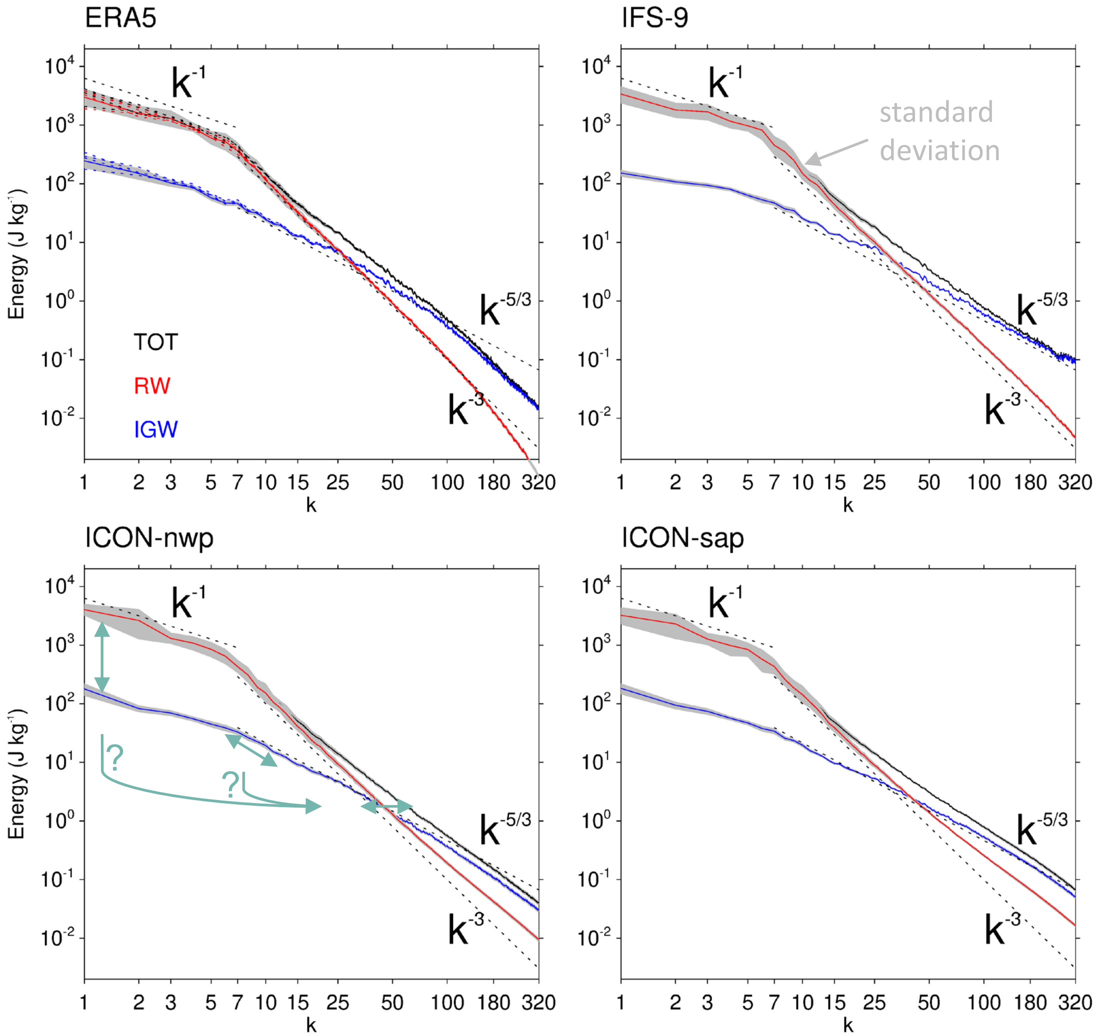
The details are different:

- Offset
- Slopes
- Crossing



Total wave energies

Energy in k = 1–320

Operational analyses struggled for a long time to have an appropriate energy partitioning between RWs and IGWs.
(Tanaka et al. 1986; Tanaka and Kung 1988; Tanaka and Ji 1995; Žagar et al. 2009, 2012)

Modern analyses: 9-15% IGW
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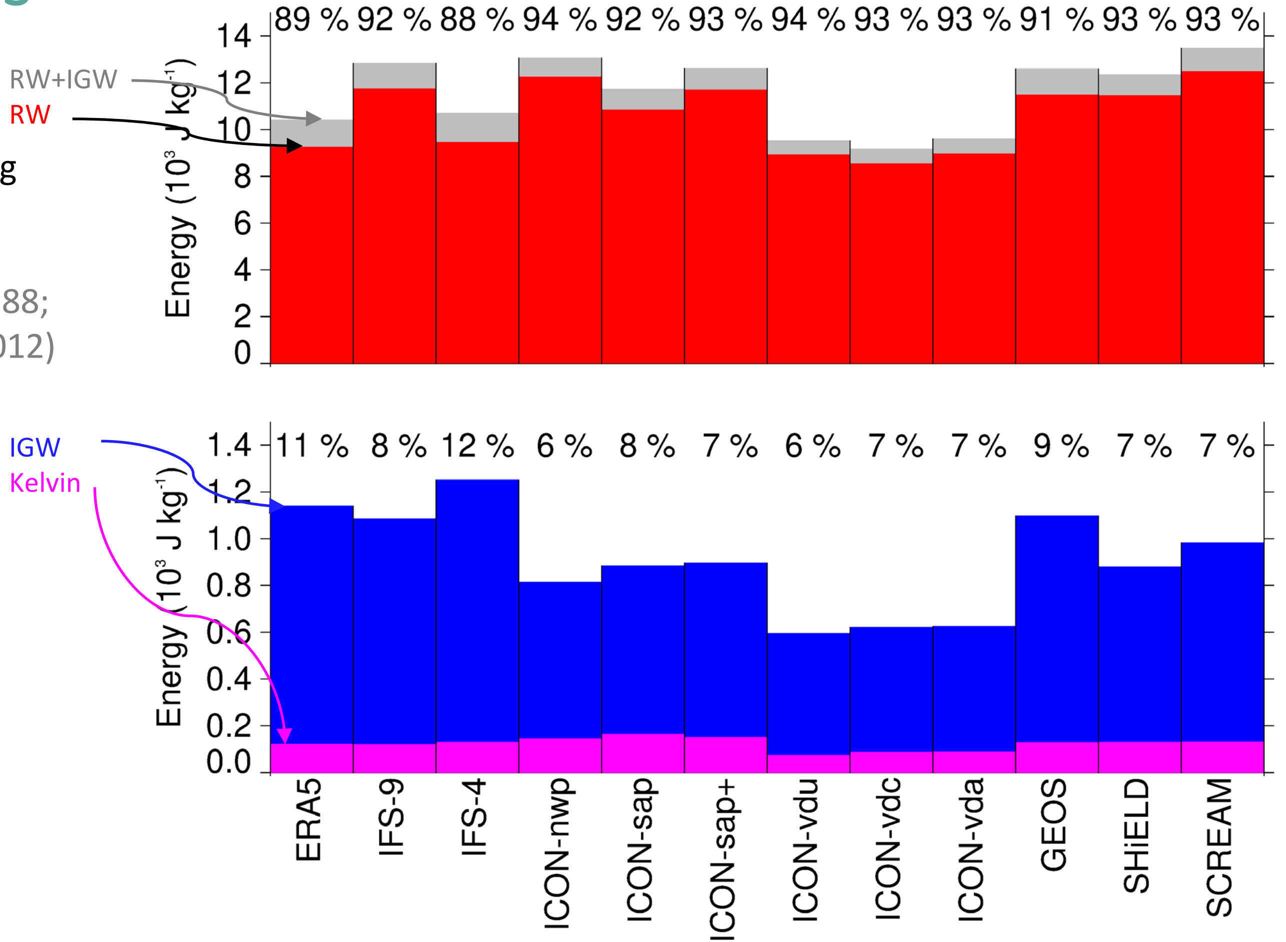

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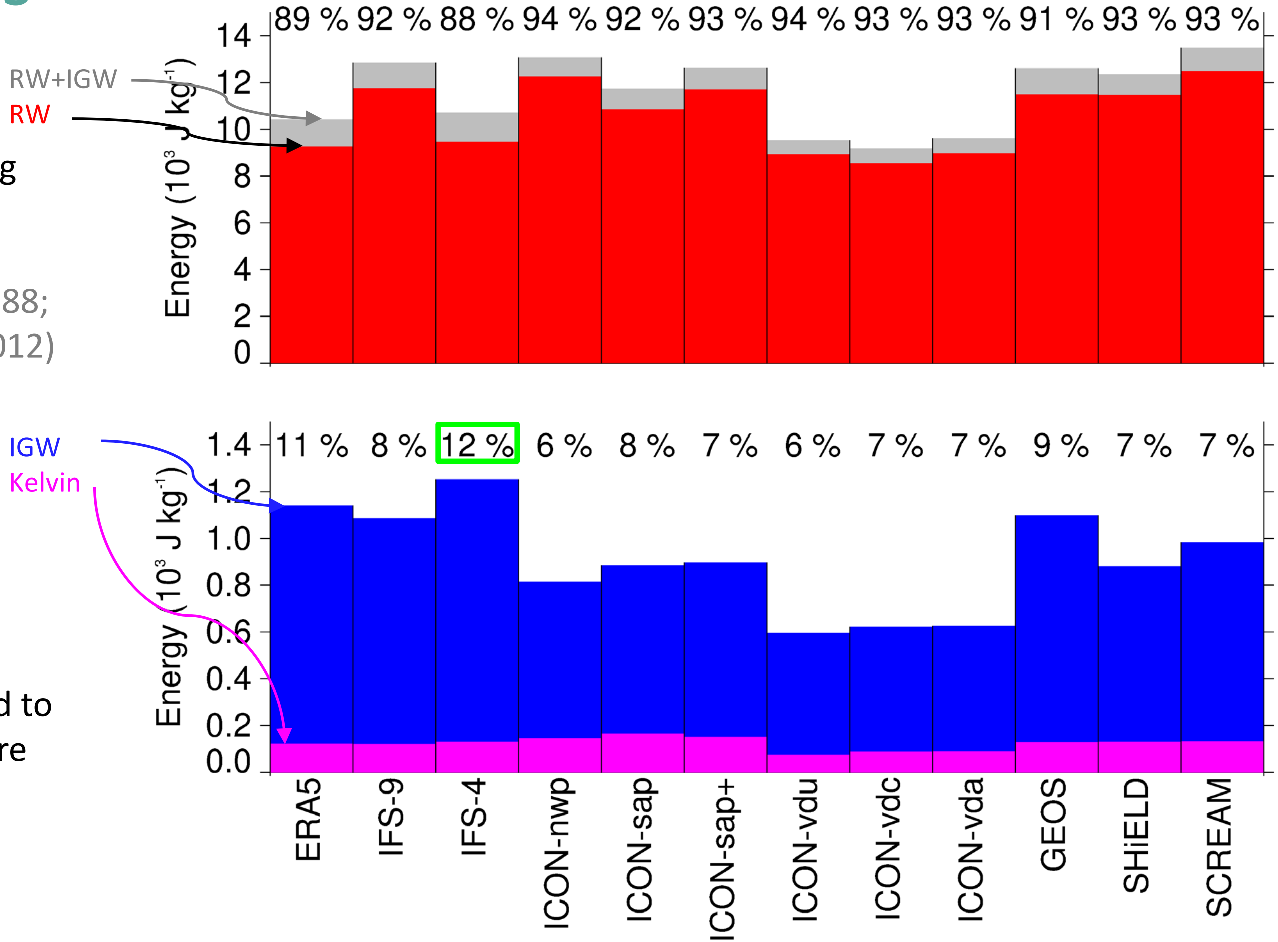

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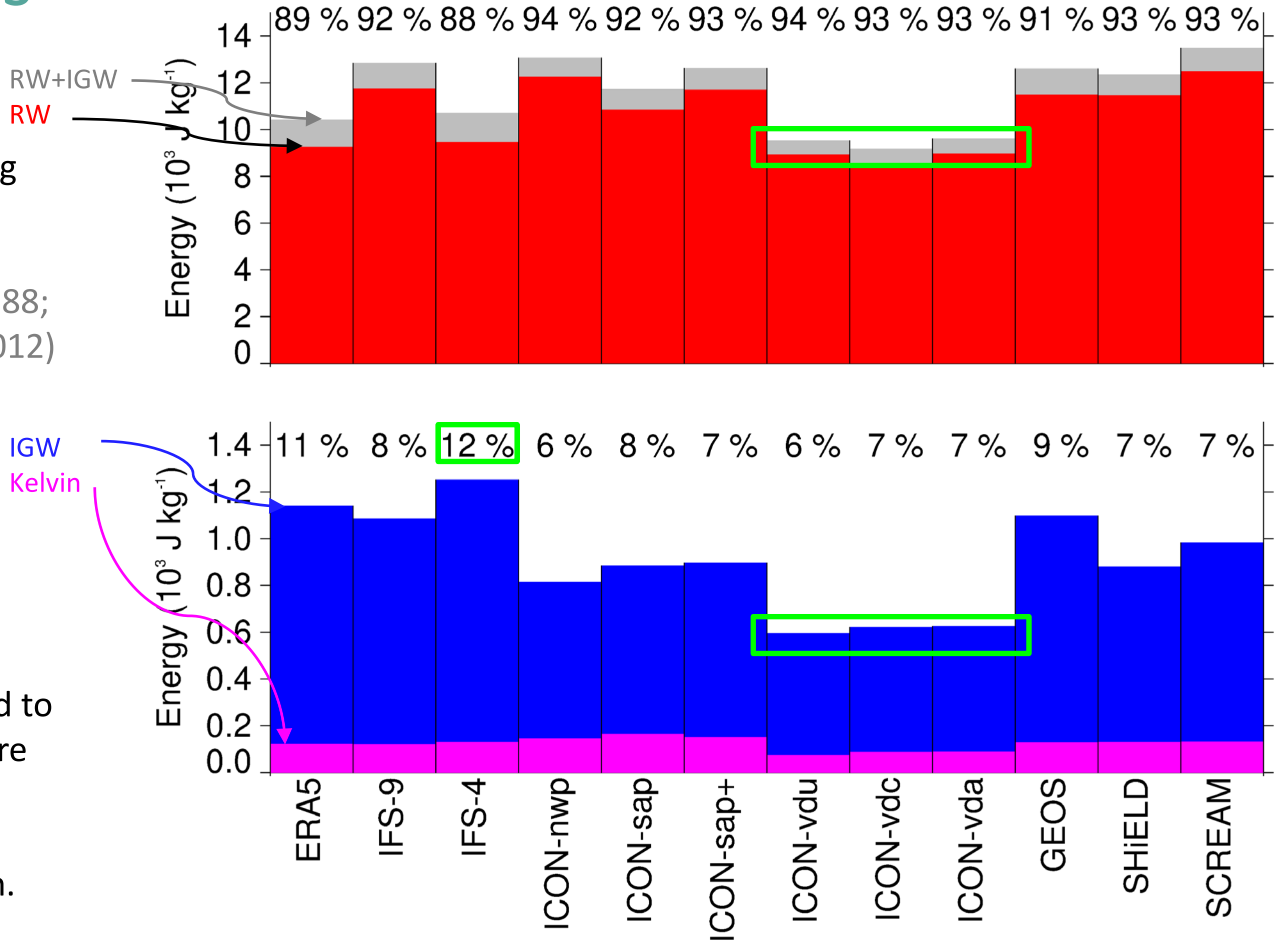
There is a sensitivity to vertical diffusion.



Spectral slopes

	TOT			RW			IGW		
wavenumbers:	1-7	8-50	51-320	1-7	8-50	51-320	1-7	8-50	51-320
ERA5	-1.1	-2.5	-2.8	-1.1	-3.0	-3.7	-0.9	-1.6	-2.6
IFS-9	-1.0	-2.6	-1.9	-1.0	-3.1	-3.0	-0.6	-1.6	-1.7
IFS-4	-1.1	-2.5	-2.2	-1.2	-3.0	-2.6	-0.9	-1.6	-2.1
ICON-nwp	-1.1	-2.6	-2.3	-1.1	-3.0	-2.6	-0.9	-1.6	-2.0
ICON-sap	-1.0	-2.5	-2.1	-1.0	-2.9	-2.4	-0.9	-1.5	-1.9
ICON-sap+	-1.1	-2.5	-2.1	-1.1	-2.9	-2.4	-0.8	-1.5	-1.9
ICON-vdu	-1.2	-2.4	-2.1	-1.2	-2.8	-2.4	-0.9	-1.5	-2.0
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flatten (RW 8-50 → 51-320)

steepen (IGW 8-50 → 51-320)

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What is the relationship to vertical velocity / relationship to convection?

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flatten →

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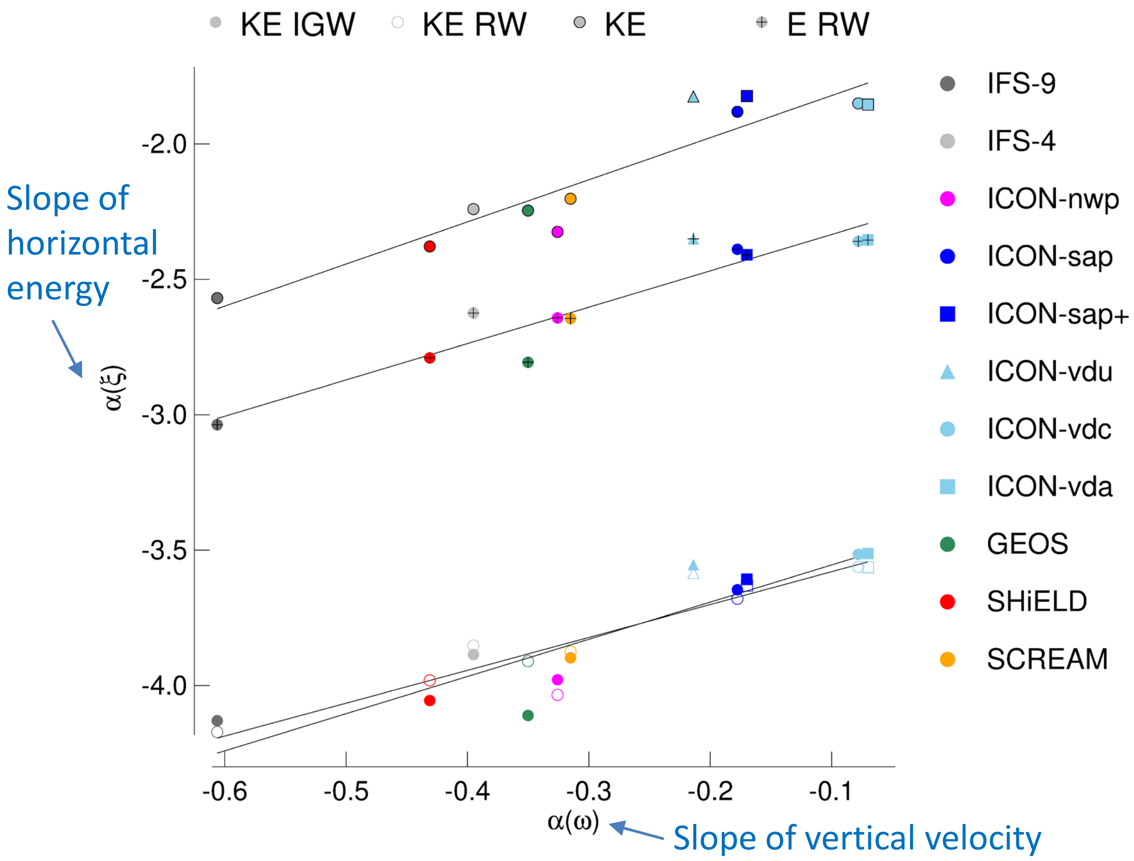
Small scales and convection



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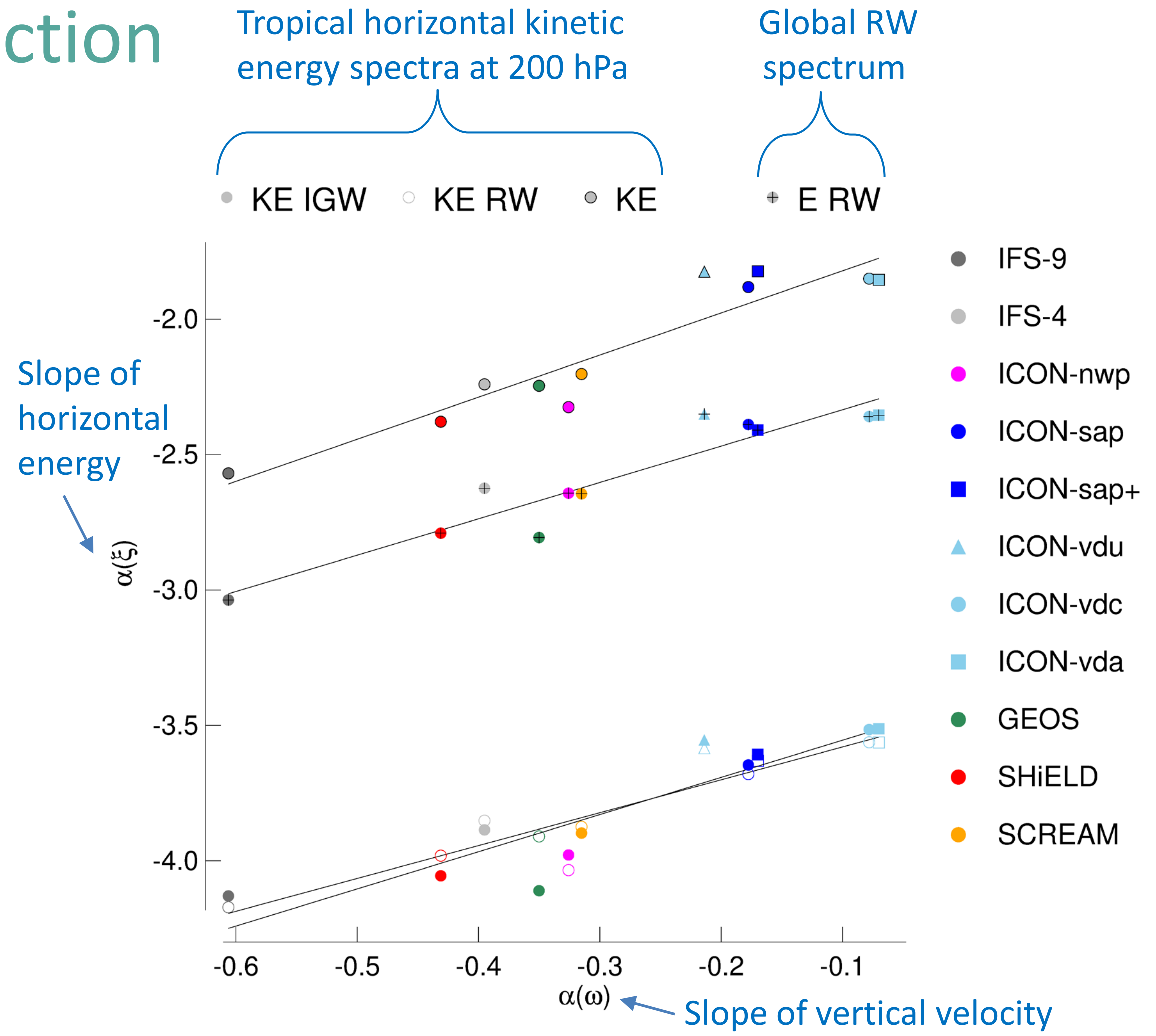

Small scales and convection

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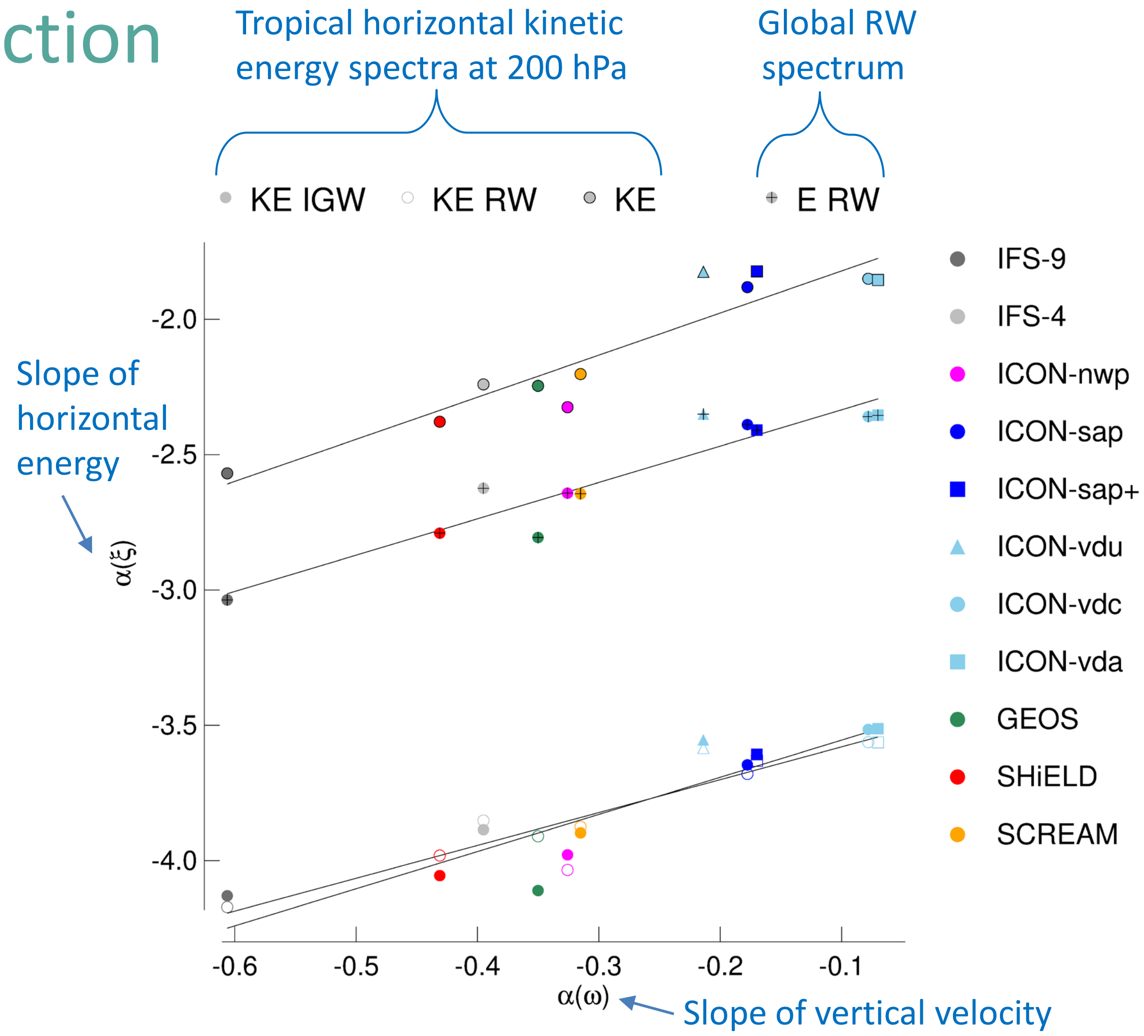
Plausible: transient tropical heating is a source of RWs that propagate within as well as out of the tropics, and of equatorially trapped IGWs.



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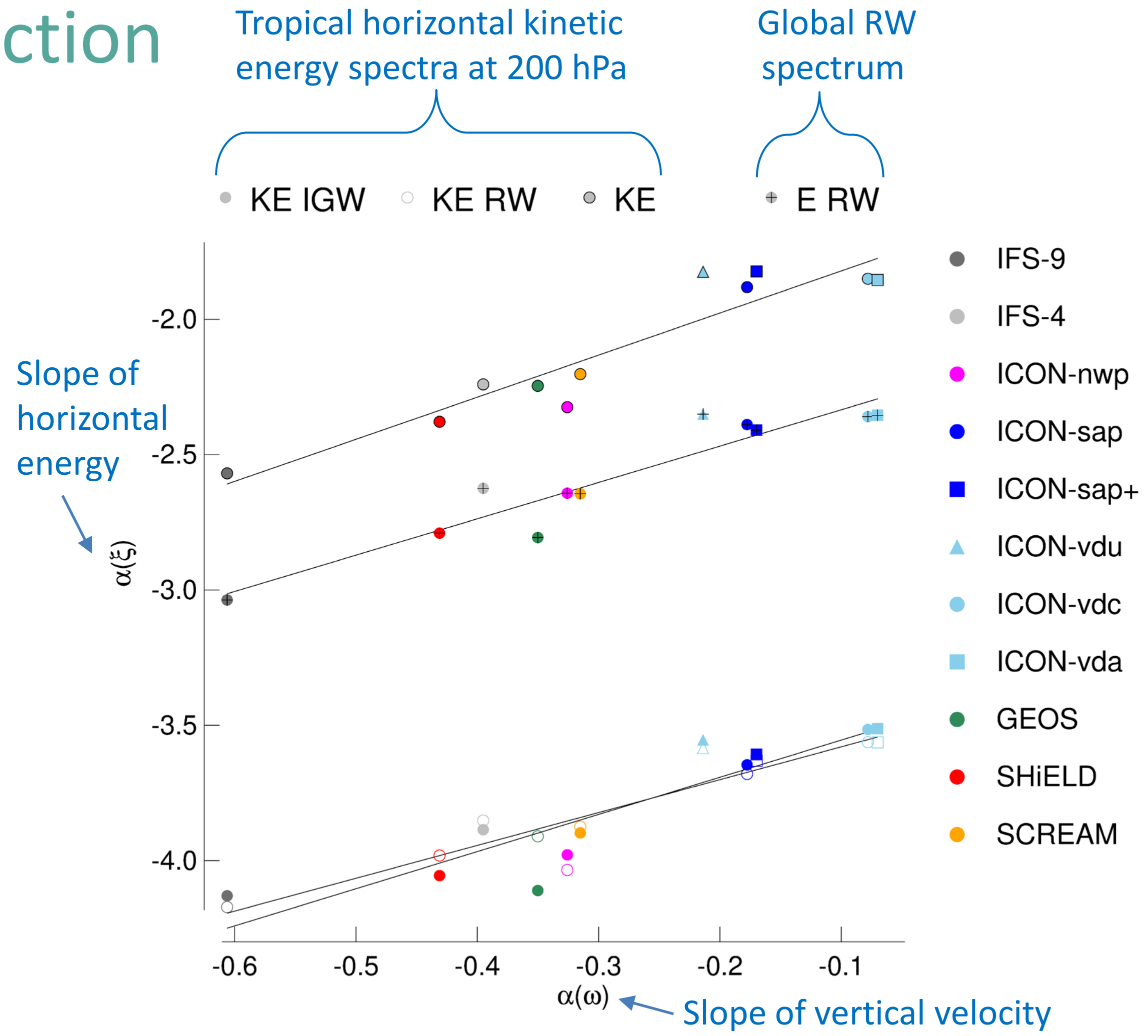
The slope of the global IGW spectrum is **not** correlated with α(ω).

Plausible: equatorial trapping, importance of extratropical IGW sources, relatively greater contribution of stratospheric levels.



Crossing scale

Crossing scales have important implications for the applicability of spatial averaging, commonly used for decomposing motions into background and waves.

	k_c	L_c (km)	
		$\phi = 0$	$\phi = \pm 45°$
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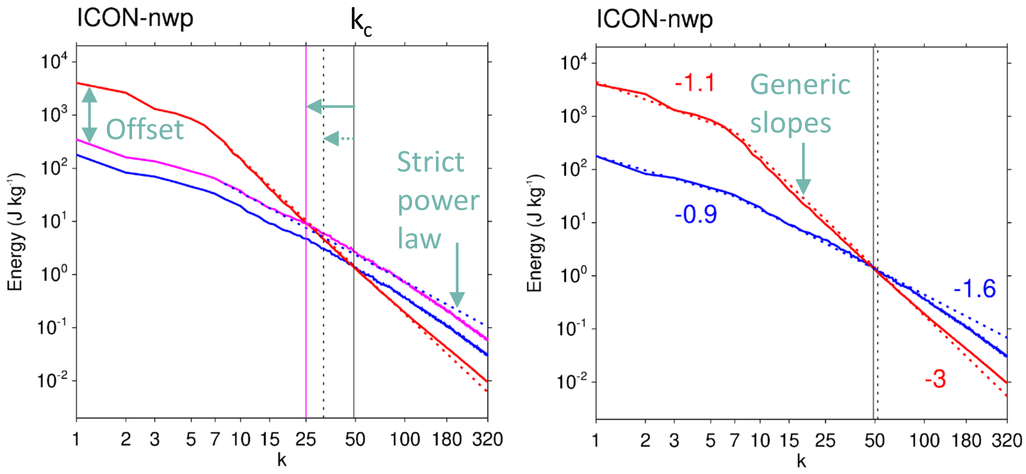

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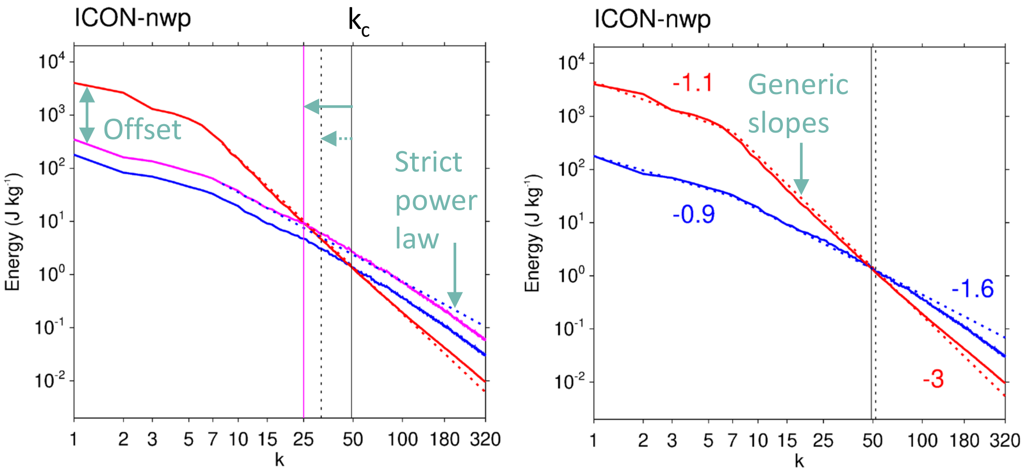

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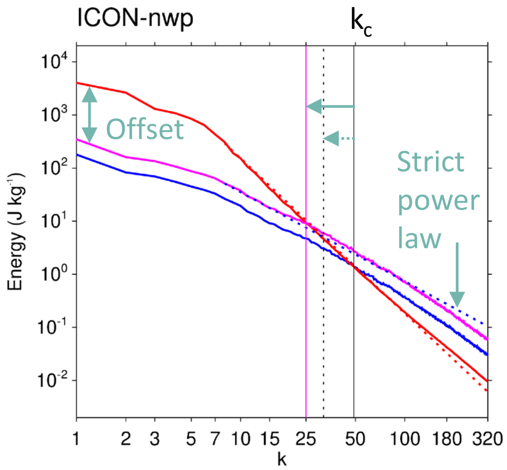

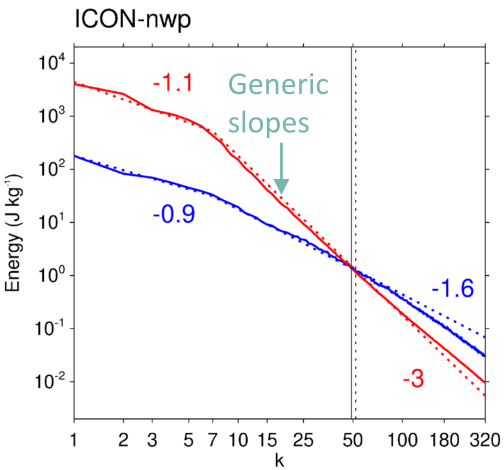

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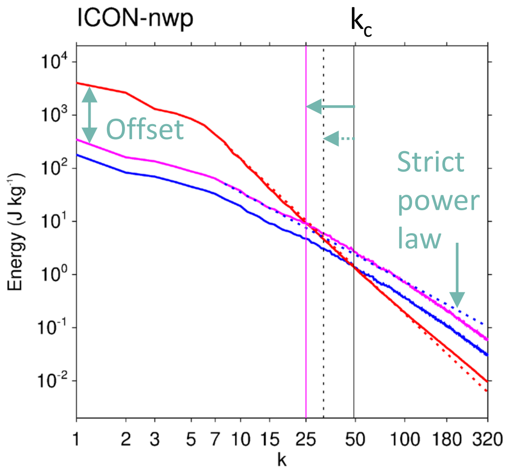

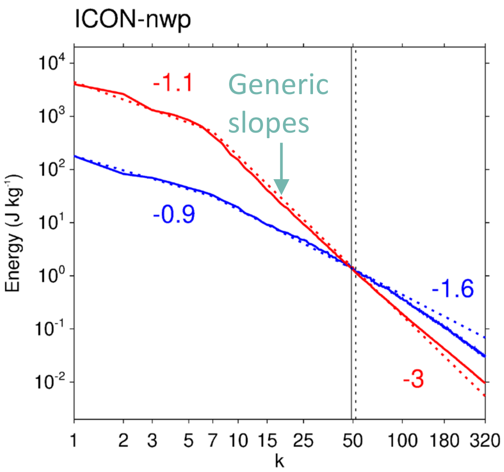

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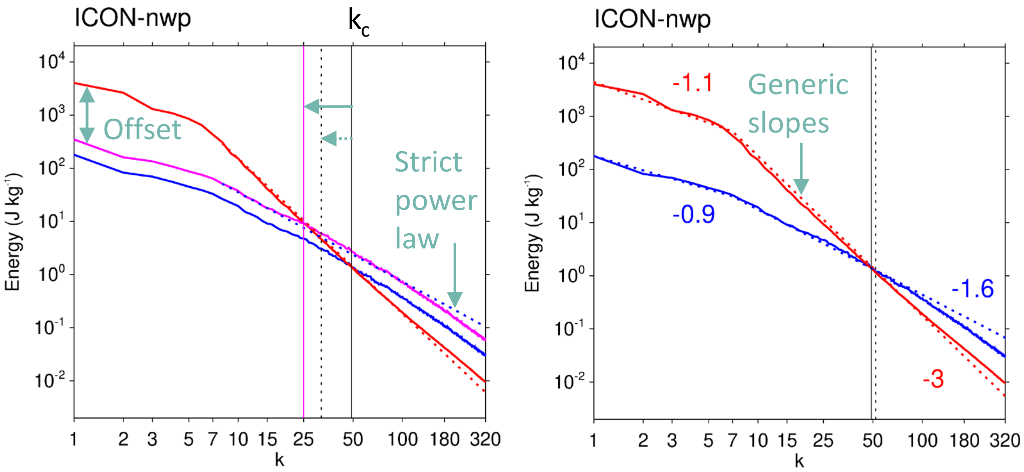

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TTE/TKE

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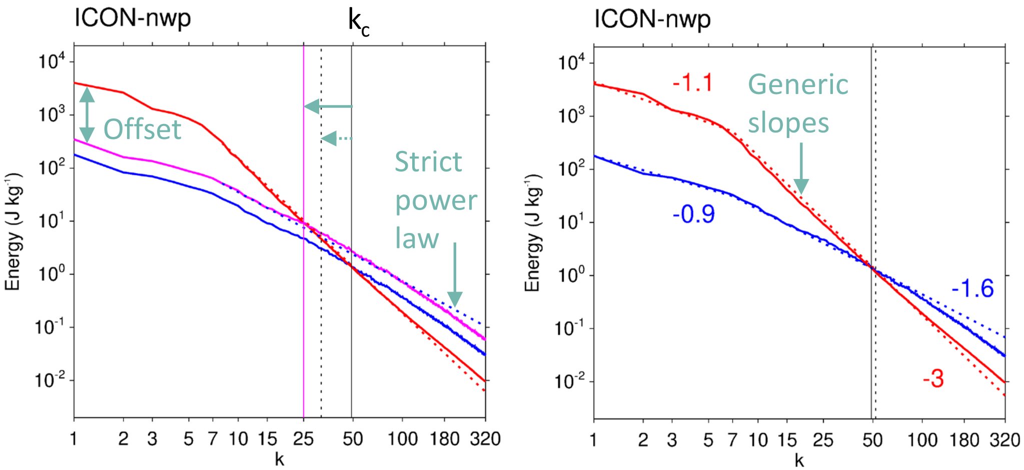

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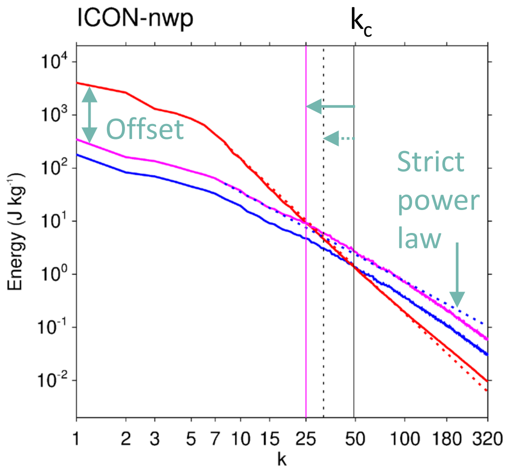

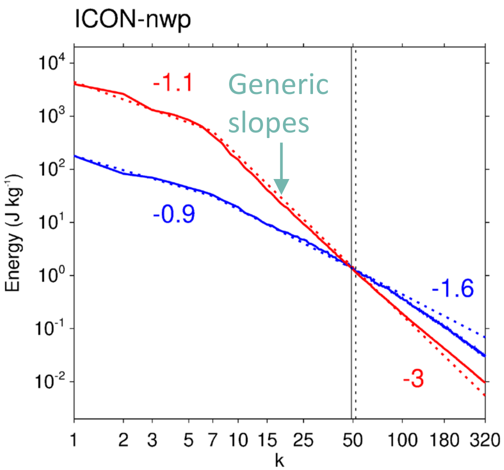

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Spectral crossing scales

- Partitioning of total energy: most important factor for determining the spectral crossing scale
- Crossing scales differ by a factor of about 2; models group by type of turbulence closure scheme (no indication for sensitivity to different horizontal or vertical resolutions, or hydrostatic versus non-hydrostatic dynamics)

Outlook

Relevance of small scales

This study looked at global horizontal plus potential available energy – **small scales** contribute very little

But:

- small scales are important for driving the global mean circulation
- horizontally short gravity waves with **large vertical velocities** | locally strong momentum flux

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Small scales differ greatly in DYAMOND! (**convection, vertical velocity, horizontal spectra**)

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Follow-up study is happening

We ran the models again ☺, writing out i) physics tendencies ii) everything required to compute non-linear spectral transfer (following Augier and Lindborg 2013) – work by Yanmichel Morfa Avalos